Astrophysics, Neutrinos, and Symmetries Town Meeting

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Executive Summary

In the past few years we have witnessed the beginning of two major intellectual revolutions in physics. One of these is the nature of physics beyond the Standard Model. For many years solar neutrino detectors have measured neutrino fluxes from the Sun that are substantially less than expected from solar models. Following very careful analysis of the models and the nuclear physics of stellar burning, the most reasonable explanation was that electron neutrinos were changing into other neutrino species before reaching Earth. Now very compelling evidence from atmospheric neutrinos indicate that neutrino oscillations undoubtedly occur. This discovery has enormous implications for nuclear and particle physics as well as astrophysics and cosmology. The other revolution is occurring in astronomy and astrophysics. New space- and ground-based telescopes have produced a veritable explosion of data covering a broad range of the electromagnetic spectrum. We are now confronted with detailed information about stellar evolution and nucleosynthesis in extreme environments. Assimilating this information into models of galactic evolution is a major challenge that will require significant input from nuclear physics.

Nuclear physics is central to both of these revolutions. Present generation solar and supernovae neutrino detectors, coupled with detectors now under construction looking at neutrinos produced at reactors and accelerators will help determine acceptable ranges for neutrino masses and mixing angles in the next few years. But it will undoubtedly take a new generation of detectors, along with double beta-decay and single beta-decay mass measurements, to fully unravel neutrino properties. This effort has important implications for many subfields of physics including astrophysics where neutrino masses and neutrino interactions with nuclei both play a major role in the origin of the elements. Also neutrinos are now known to be crucial in the physics of supernovae explosions and the subsequent transmutation of nuclei via the r-process.

The observation of neutrino oscillations and the subsequent need for new physics beyond the Standard Model underscores the importance of pursuing low-energy symmetry experiments aimed at testing the model. Nuclear physics has a long tradition in this subfield and members of our community are presently working on problems in nuclear and neutron beta decay, muon decay, parity violation in electron and hadron induced interactions and atomic systems, and searches for time reversal violation in neutrons, atoms and molecules. During the next decade low-energy symmetry tests offer high discovery potential for probing this new physics.

During the decade of the 1990's, nuclear physics invested in new detectors and developed new technology in support of experiments in astrophysics, neutrinos and symmetries. It is crucial that we capitalize on these investments. But it is equally important to plan for the future. At the Oakland Town Meeting, a road map was developed that will allow these subfields to make significant physics contributions in the next decade. New facility requirements are summarized by the first three recommendations from the Town Meeting. Two recommendations request new facilities and detectors for neutrino physics and one requests new facilities for the next generation of fundamental symmetry tests with neutrons. The fourth recommendation underscores the need to improve the theory support for these activities. This problem has become a critical one since the number of active theorists in our subfields has declined to a point where many problems simply cannot be addressed. The fifth recommendation stresses the need for cooperation between the fields of nuclear, high-energy and atomic physics and astrophysics to ensure that experiments which cut across traditional funding boundaries are supported.

The first recommendation from the Town Meeting is for a new underground laboratory in the U.S. The facility would house the next generation solar neutrino and double beta-decay experiments. A task force jointly funded by DOE and NSF is now studying the options for such an underground laboratory and a preliminary report which includes estimates for construction and operations costs should be available prior to the long range plan working group meeting in March, 2001. The second and third recommendations are tied, in part, to the construction of the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The second recommendation requires action soon if we are to capitalize on the SNS by constructing a cold-neutron beam end station there. It further stresses the need for continued development of ultra-cold neutrons (UCN) and the eventual implementation of a dedicated UCN source. The third recommendation – a neutrino facility to be built next the SNS beam dump – also requires quick action in order for civil construction to begin on a time scale that is compatible with the SNS schedule. The capital expense involved in building the cold-neutron beam end station is small. The initial funds required for the neutrino facility –

ORLaND – also are modest. The physics that will come from implementing these three recommendations makes them extremely cost effective.

The recommendations from the Town Meeting are given below. Details of the physics that led to them are given in the report from the Town Meeting.

Recommendation #1: Nuclear physics must build on its successes with low-energy neutrinos by initiating work on the next generation of neutrino experiments. These efforts are not only key to understanding the nuclear physics of stars and supernovae, but could profoundly influence cosmology, astrophysics and particle physics. Our community must spearhead an effort to create a deep underground multipurpose laboratory that could accommodate the essential new solar-neutrino and double-beta-decay experiments, as well as others of interest to the broader scientific community.

Recommendation #2: Intense sources of pulsed cold neutrons and UCN's must be pursued. Nuclear physics should seize the opportunity for fundamental neutron physics at the SNS by investing in a high-intensity, pulsed cold neutron beamline. Concurrently, development of a high-intensity ultra-cold neutron source should be pursued vigorously with the goal of creating a national UCN user facility.

Recommendation #3: Nuclear physics should take full advantage of the unique opportunities for neutrino physics at the SNS by constructing the ORLaND neutrino experimental facility.

Recommendation #4: Additional theoretical manpower is an essential element in the future program in neutrino astrophysics and fundamental symmetries. It is critical to establish mechanisms at the predoctoral, postdoctoral and faculty levels in order to attract and retain the best young people to work on the problems relevant to nuclear astrophysics, fundamental symmetries and closely related areas of nuclear structure. In addition, new initiatives should be launched to develop a standard model of core collapse supernovae, an outstanding "grand challenge" problem in nuclear physics and astrophysics.

Recommendation #5: Nuclear physics should continue to support members of our community who collaborate on relevant experiments funded primarily by other subfields. Further, nuclear physics must work closely with atomic physics and high energy physics to ensure that experiments which cut across traditional funding lines are supported.

1 Introduction

Nuclear physics has a long tradition in neutrino physics, astrophysics and studies of fundamental symmetries. Landmark events include the explanation of stellar evolution; the chlorine solar neutrino experiment, which created the field of neutrino astrophysics; and, in nuclear β decay, the introduction of the neutrino to conserve energy, the discovery of parity-violation in the decay of ^{60}Co and the subsequent precision tests that contributed to the experimental foundations of the Standard Model of the electroweak interaction. With the inclusion of QCD, the Standard Model provides the basic theoretical framework for nuclear physics. Nuclear scientists use quantitative tools derived from it to probe nuclei and nuclear currents, to study aspects of nucleon structure such as strange sea quark effects, and to understand the nuclear physics of extreme environments such as the big bang, supernovae and neutron stars. Testing the model and searching for physics beyond it is thus central to nuclear physics, as it is to particle physics, atomic physics and cosmology. Recent exciting discoveries in neutrino astrophysics – a subfield pioneered by nuclear physics – provide the first very strong evidence for "new" physics beyond the Standard Model.

Physics is currently undergoing two major intellectual revolutions.

One of these is the nature of physics beyond the Standard Model. From a conceptual standpoint, there are many indications that the model is incomplete – the baryon asymmetry in the universe, the origin of electric charge quantization, and the hierarchy of elementary particle masses cannot be fully understood within the Standard Model. The search for new physics in nuclear, particle, and atomic physics is strongly motivated by these conceptual questions. It is significant that the first clear *experimental* evidence for new physics has come from a discipline initiated by nuclear physics – neutrino astrophysics. Measurements of the atmospheric neutrino flux have provided compelling, direct evidence for the occurrence of neutrino oscillations, which are not part of the Standard Model. With SNO and other new solar neutrino experiments, a new generation of tritium beta-decay and massive double beta-decay experiments, and opportunities like K2K, KamLAND, and MiniBooNE to probe oscillations with accelerator and reactor neutrinos, the next decade promises to be rich with scientific discoveries. The pattern of neutrino masses and mixing should be revealed, thereby guiding efforts to formulate a new Standard Model. Nuclear science is poised to play a central role in delineating the fundamental implications of this first revolution.

A second revolution is occurring in astronomy and astrophysics: advances are allowing observers to probe the universe with increasing precision and in a wide band of wavelengths. Among the issues that may be clarified in the next decade are the nature of dark matter and dark energy; the origin of the elements; the evolution of large scale structure; and the physics of extreme environments, including supernova explosions, neutron stars, and cosmic rays with energy in excess of 10^7 TeV. Neutrinos are central to much of this physics. Atmospheric neutrino results already demonstrate that neutrinos are at least as important as the stars in their contribution to the mass of the universe. Neutrino masses will become important cosmological parameters as more precise microwave and large-scale structure maps of the universe are made. Active-sterile neutrino oscillations in the early universe can change the effective number of neutrino species and hence the big-bang nucleosynthesis yield of ^{4}He. Neutrinos control the proton-neutron chemistry of supernova ejecta in which we believe the heavy r-process elements are synthesized, and are directly involved in the synthesis of certain nuclei. Just as solar neutrinos allow us to probe conditions in the solar core, the supernova neutrino "light curve" may help us better understand such stellar explosions, and may carry information on the state of the high-density nuclear matter in the proto-neutron star. High energy neutrinos may allow us to look inside the universe's most energetic central engines. Conversely, these new environments will provide unprecedented opportunities to test basic neutrino physics. For example, matter effects for supernovae neutrinos can dramatically enhance oscillations that would otherwise be unobservable.

Nuclear physics has an opportunity to expand its roles in both revolutions.

1.1 Neutrinos and Nuclear Astrophysics

A new initiative in nuclear astrophysics, which would encompass the neutrino physics discussed above, is an outstanding opportunity for the field. Such an initiative could include other physics now under discussion in the Long Range Plan process, such as the Rare Isotope Accelerator, with its strong program of laboratory astrophysics. Clearly the impact of future studies of the nuclear structure of the r-process will be enhanced if nuclear physicists can at the same time understand the supernova neutrino physics that controls the r-process path. This synergism between the nuclear structure and supernova neutrino studies must be stressed. Progress on both fronts is essential to affirm any theoretical development of a standard model for core-collapse supernovae and to understand the associated nucleosynthesis.

Despite the interest in and promise of non-accelerator neutrino physics, U.S. physicists have had to overcome obstacles in mounting major experiments. Following the first experiment at Homestake, important ideas have come from the U.S. community (e.g., SAGE/GALLEX and SNO), but the detectors have been built elsewhere, with U.S. scientists as participants. Similarly, though U.S. physicists are active in the field, no large-scale double beta decay experiment is currently running in the U.S. Two facilities within the U.S., WIPP and Soudan, offer the potential to mount underground experiments at modest depths (1700 and 2100 m.w.e., respectively) but there is no deep facility available.

Here Europe and Japan have moved ahead of us. Italy's Gran Sasso laboratory was created to foster underground experiments in Europe. It has become a major center, encouraging new ideas in underground physics and drawing experiments from across Europe and elsewhere. It is currently considering expansion of two additional caverns and a separate access tunnel. In Japan the Kamioka proton-decay experiment, contemporaneous with the U.S. IMB experiment, was followed by Super-Kamiokande, an effort that has had a profound influence through its solar and atmospheric neutrino discoveries.

Now is the time to create a deep underground multipurpose facility in the U.S. that will allow the international community to carry out the next generation of solar/supernova neutrino and double beta decay experiments. Because this national facility could also serve many of the needs of experiments to study dark matter, long baseline neutrino oscillations, supernovae, and nucleon decay, it is important to collaborate with colleagues from particle physics and astrophysics. The announced closing of the Homestake Mine in December 2001, coupled with the interest of the state of South Dakota in converting this to a national scientific facility, could provide such a deep (4850-8000 ft) hard-rock site. Alternatively, there may be an opportunity at San Jacinto to create a deep site with horizontal access.

1.2 Tests of Fundamental Symmetries

Outside the field of neutrino physics, the search for signatures of new physics in nuclear, particle, and atomic physics continues to extend its reach into the model space of new physics scenarios. Owing in large part to improvements in experimental precision, low-energy experiments in nuclear physics are now sensitive to new physics at the TeV scale and beyond. The discovery of neutrino oscillations suggest that additional signatures of new physics may lie within the reach of other, high-precision low-energy experiments. The recently completed measurement of the muon g-factor, for example, indicates a 2.6σ deviation from the Standard Model prediction. If conventional hadronic effects cannot account for this discrepancy, then the most likely explanation is supersymmetric loop contributions. Supersymmetric grand unified theories predict the existence of a permanent electric dipole moment of the neutron at scales only one or two orders of magnitude beyond the present limits. Superallowed Fermi nuclear β-decay and K_{e3} decays imply that that Cabbibo-Kobayashi-Maskawa matrix is non-unitary at the two sigma level. This non-unitarity could result from right-handed gauge interactions, B-L violating exchanges of squarks and sleptons, or the presence of leptoquarks. More precise determinations of neutron β-decay asymmetry parameters, as well as a new determination of V_{us} from K_{e3} decay, would help clarify this situation. The possibilities for new neutron EDM and β-decay measurements are especially promising in light of recent technical advances with ultra-cold neutrons, including the production of a world record density and demonstration of the first magnetic trap. Deviations from Standard Model predictions may also be uncovered in parity-violating ee and ep scattering, muon decay, $\mu \to e$ conversion in nuclei, low-energy beta-decay experiments, and EDM's of radioactive atoms. Experiments are underway in all of these areas attempting to push sensitivities to unprecedented levels. Prior to the first results from the LHC near the end of this decade, these experiments offer some of the best opportunities available for further probing the new physics that the neutrino experiments are finding. While the basic infrastructure – accelerators and detectors – is in place to carry out many of these measurements, new neutron source capabilities are needed to realize the full impact of fundamental symmetries studies. Indeed, during this window of opportunity, it is imperative that nuclear physics renew its commitment to these experimental efforts.

2 Principal Recommendations

Neutrino experiments in nuclear physics are essential to our understanding of the properties of neutrinos. The new discoveries and their theoretical interpretation will affect our understanding of nucleosynthesis, supernovae, astrophysics, particle physics, and cosmology. The current generation of solar neutrino experiments is expected to provide information needed to separate the ^{8}B neutrino flux into electron and heavy flavors. The next major push in this area must involve active detectors capable of determining the flux and flavor of the low-energy *pp* and ^{7}Be neutrinos, since most candidate solutions to the solar-neutrino puzzle affect this portion of the spectrum in distinctive ways. Several detectors with the necessary characteristics are well along in development. Remarkable progress has occurred in neutrinoless double beta decay measurements over the past two decades – a factor of two increase in lifetime limits every two years. But the present generation experiments have now reached a limit, $\sim 10^{25}$ years, imposed by current detector sizes (~ 10 kg). There are now urgent reasons for probing Majorana neutrino masses at the 0.03-0.10 eV level, requiring much larger detectors. Several excellent experiments have been proposed, some of which are technically well developed. It is equally important to make direct neutrino mass measurements at the sub-eV level. A new measurement of tritium β decay remains the most promising way to reach this range of sensitivity. It is imperative to move these next-generation projects quickly through the R&D phase, so that the most promising detectors can be identified and launched as full-scale experiments. Of course, the solar neutrino and double beta-decay experiments must be located in deep, well shielded, underground locations to reduce limiting cosmic-ray backgrounds.

Recommendation #1: Nuclear physics must build on its successes with low-energy neutrinos by initiating work on the next generation of neutrino experiments. These efforts are not only key to understanding the nuclear physics of stars and supernovae, but could profoundly influence cosmology, astrophysics and particle physics. Our community must spearhead an effort to create a deep underground multipurpose laboratory that could accommodate the essential new solar-neutrino and double-beta-decay experiments, as well as others of interest to the broader scientific community.

At present, activities in fundamental cold and ultracold neutron physics are limited to beam lines at NIST and LANSCE. These facilities are oversubscribed and will not be able to accommodate the full range of next generation neutron measurements. Moreover, most new measurements will be limited in precision by the available cold neutron beam intensities. Thus, a need exists for development of a coherent set of new, intense cold and ultracold neutron source capabilities in the U.S.

The implementation of a pulsed cold neutron beam line at LANSCE provides a first step in this process. The Spallation Neutron Source now under construction at Oak Ridge National Laboratory offers nuclear physics a unique opportunity to develop a world class cold neutron beam end station. Cold beams at the SNS would provide the flux needed to carry out extremely important measurements such as a new determination of the asymmetry parameters in polarized neutron β decay – an important test of CKM unitarity – and studies of parity violation in $n-p$ capture and n spin rotation. Indeed, nuclear and hadronic parity-violation offers the only context in which to study the $\Delta S = 0$ nonleptonic weak interaction and the mechanism through which weak interactions of quarks appear in the guise of hadrons. In addition, pulsed cold neutron sources may be used in providing UCN's for some experiments.

Since the completion of the last LRP, enormous technical advances have been made in the field of ultracold neutron studies. Superthermal sources of UCN's have been demonstrated at NIST and LANSCE, with world record densities (100 UCN/cc) achieved at LANSCE. Magnetic trapping of UCN's has also been demonstrated at NIST, leading to prospects for a factor of ten or more improvement in the precision of the neutron lifetime. These developments open the way for considerably more powerful probes of CP violation with neutron EDM measurements (one to two orders of magnitude) and additional tests of CKM unitarity with neutron β decay. The road map for a UCN user facility should include a UCN development project at LANSCE and/or NIST, followed by a larger scale facility to be sited at RIA, SNS, LANSCE or some other location.

Recommendation #2: Intense sources of pulsed cold neutrons and UCN's must be pursued. Nuclear physics should seize the opportunity for fundamental neutron physics at the SNS by investing in a high-intensity, pulsed cold neutron beamline. Concurrently, development of a high-intensity ultracold *neutron source should be pursued vigorously with the goal of creating a national UCN user facility.*

Another extremely important byproduct of the SNS is a stopped pion neutrino source of unusual characteristics: a flux in excess of that achieved at LAMPF, a pulsed time structure similar to that of the ISIS facility at Rutherford Laboratory, and an unusually low contamination of $\bar{\nu}_e$ (important for oscillation tests). The ORLaND collaboration has proposed exploiting this $\sim$ \$1B new accelerator by constructing a neutrino experimental hall near the beam stop. A variety of neutrino experiments – new oscillation tests, measurements of neutrino-nucleus cross sections important to supernova physics, tests of isoscalar axial currents – could be tackled with such a facility. Results from such experiments would directly impact our understanding of the role of neutrinos in supernova physics, provide sensitive tests for physics beyond the Standard Model and aid in understanding a number of issues in present and future solar neutrino experiments.

Recommendation #3: Nuclear physics should take full advantage of the unique opportunities for neutrino physics at the SNS by constructing the ORLaND neutrino experimental facility.

There has been a tradition of very close interactions between theorists and experimentalists in the physics represented at this Town Meeting. Outstanding examples include the nuclear physics of the pp chain, radiative corrections to Fermi β decay and the Jlab parity program, the nuclear structure physics of $\beta\beta$ decay and hadronic parity violation, the supernova mechanism and associated nucleosynthesis, and the nuclear physics responsible for atomic electric dipole moments. These problems have stimulated some of the most important developments in nuclear structure theory including recent improvements in the foundations and technology of the shell model, the use of exact methods such as Green's function Monte Carlo and new approaches such as effective field theory.

But the existing theory community, despite its high quality, is too small. The expertise to attack many of the important problems listed above – often requiring a combination of skills in electroweak interactions, astrophysics, and nuclear structure – resides in only a limited number of individuals. Much of the recent growth in nuclear theory has occurred through targeted efforts associated with our two major facilities, Jlab and RHIC. The faculty bridge programs undertaken by JLab and the RIKEN-BNL Theory Center have clearly benefitted theory as a whole but they may have further restricted opportunities in areas such as nuclear astrophysics, neutrino physics, and low-energy weak interactions where incentives were lacking to build new efforts. It is now essential to develop a similar innovative program to attract some of the best young people to theory positions in these other areas of nuclear physics.

The mechanism for bringing young theorists into the field could occur under a national society of nuclear theory fellows. It could include several elements: the creation of new junior faculty positions through bridge arrangements similar to those associated with JLab and RHIC; the creation of permanent research positions associated with experimental groups both at universities and national labs; and support for additional post-docs and graduate students to work with faculty and research staff. The addition of new positions in university settings is especially important for attracting talented students into the field. In order to provide some coherence and avoid the possibility that fellows become isolated, the new effort could include an annual summer research program, analogous to the Aspen programs in particle physics. All fellows, and other interested theorists, would be encouraged to attend this program and provided with travel support.

In addition to the need for additional individual investigators, some theory problems require large-scale efforts. One outstanding example is the construction (and eventual experimental verification) of a standard model of core collapse supernovae. This problem encompasses nuclear theory, astrophysics, and computer science. Its solution requires modeling of: (1) the nuclear equation of state up to at least four times nuclear density; (2) three-dimensional hydrodynamics – in particular, convection, and rotation – and shock wave propagation; and (3) the neutrino transport and neutrino-nucleus microphysics that we believe is crucial to both the development of the explosion and the associated nucleosynthesis. Supernova physics is benefitting from recent developments in nuclear structure theory and will serve as an important stimulus for further shell-model work. A standard supernova model is needed to make full use of the nuclear-structure information that RIA will provide along the r-process path. It is also needed to understand detailed abundance patterns that have recently come from Hubble Space Telescope and other studies of metal-poor stars enriched in r-process metals. Finally, it is essential if we are to exploit the next galactic supernova as a laboratory for new neutrino physics – unique signatures of neutrino mass and matter-enhanced oscillation are possible with supernova neutrinos.

Recommendation #4: Additional theoretical manpower is an essential element in the future program in neutrino astrophysics and fundamental symmetries. It is critical to establish mechanisms at the predoctoral, postdoctoral and faculty levels in order to attract and retain the best young people to work on the problems relevant to nuclear astrophysics, fundamental symmetries and closely related areas of nuclear structure. In addition, new initiatives should be launched to develop a standard model of core collapse supernovae, an outstanding "grand challenge" problem in nuclear physics and astrophysics.

Neutrino physics and studies of fundamental symmetries lie at the intersection of nuclear, particle, atomic and astrophysics. Collaborations often cross subfield lines; the different experimental skills within these subfields are a source of vitality for the fields. Examples are the AMANDA detector for observing high-energy astrophysical neutrinos; the next-generation proton-decay detector being planned by particle physics, where nuclear physics interests might focus on exploiting such a massive detector for solar or supernova neutrino detection; dark matter searches, which share many technical challenges with double beta decay searches; parity and time-reversal violation measurements in atomic and molecular systems; fundamental measurements of muon, pion, kaon and hyperon decays (such as the determination of V_{us} from K_{e3} decays). Experiments in these areas often fall in the boundary between funding agencies and thus have no stable support base. The parity violation and edm measurements using atomic physics techniques are recent examples. These fundamental symmetry tests are attacking very similar physics as other experiments in nuclear physics since, for example, they probe CP violation (in the nucleus, neutron or electron) and provide a determination of the nuclear anapole moment. It is important for the nuclear physics community to support experimental efforts that intersect with other fields because they are relevant intellectually and bring new technology into our own field. Our community should work with both atomic physics and high energy physics in these areas of physics overlap to ensure that high quality experiments are properly funded.

Recommendation #5: Nuclear physics should continue to support members of our community who collaborate on relevant experiments funded primarily by other subfields. Further, nuclear physics must work closely with atomic physics and high energy physics to ensure that experiments which cut across traditional funding lines are supported.

3 Nuclear Astrophysics and Neutrino Subfield Summaries

This is an exciting period for neutrino physics and nuclear astrophysics. Substantial progress has been made in both subfields since the last Long Range Plan including one of the most profound discoveries in recent years – we now have clear evidence of neutrino oscillations. And the prospects for new discoveries in the near future are extremely promising. Members of these communities gathered first at a 3-day neutrino pre-town meeting held in Seattle in September, 2000 and then at the Oakland town meeting in November, 2000. The following sections summarize the presentations and discussion at these meetings.

3.1 Solar Neutrinos

The pattern of solar neutrino fluxes that has emerged from current experiments, combined with the atmospheric neutrino evidence for neutrino mass, strongly suggests that the solar neutrino problem is due to neutrino oscillations. The current interpretation of the Super-Kamiokande atmospheric results favors $\nu_\mu \to \nu_\tau$ oscillations. Thus solar neutrinos may be the best tool for probing the new properties of the first-generation ν_e.

What scientific questions is this subfield trying to answer?
There are five principal questions driving the field:
• What nuclear physics governs energy production in our sun's core and in other stars? Is our understanding of stellar evolution quantitative?
• What is the origin of the solar neutrino problem?
• Do electron neutrinos oscillate and, if so, to what?

• What information about neutrino masses and mixing angles can be extracted from solar neutrino experiments?
• Do neutrinos have other non-standard-model properties, such as magnetic moments or flavor-changing interactions?

What is the significance of this subfield for nuclear physics and science in general?
• The nuclei we study were created in stars and in stellar explosions. Solving the solar neutrino problem is the first step in demonstrating we understand stellar evolution and nucleosynthesis quantitatively. It opens the door to further studies in more explosive environments, where nuclei exist in conditions not yet found in the laboratory.
• In the past two decades physics has made an extraordinary investment in both accelerator and nonaccelerator experiments to probe the Standard Model. It now appears that the first sign of new physics involves the neutrino. Nuclear physicists started the field of neutrino astrophysics with the chlorine experiment and are now positioned to contribute to major discoveries in particle physics.
• A knowledge of neutrino masses is crucial to the next generation of precision cosmology experiments. It is already established that neutrinos are an important part of the universe's mass, at least comparable to the visible stars. Neutrino mixing can alter the spectrum of cosmological neutrinos.
• Neutrino properties are crucial to understanding much of nuclear astrophysics, including the supernova mechanism and the r-process.

What are the achievements of this subfield since the last long range plan?
• In 1995 Super-Kamiokande was nearing completion. It has now produced results on the ^{8}B neutrino spectrum of unprecedented accuracy and found very strong evidence of atmospheric neutrino oscillations.
• In 1995 SNO was under construction. Today it is operating, has surpassed its background goals, and has observed the ^{8}B neutrino spectrum.
• In 1995 no neutrino source of sufficient intensity was available for measuring the responses of solar neutrino detectors. GALLEX and SAGE have now been tested with ^{51}Cr neutrino sources, verifying the nuclear cross sections and the efficiency of the chemistry.
• In 1995 Borexino's Counting Test Facility was under construction. The CTF experiment was successful, and construction of the full detector is now

well underway.
• KamLAND, an experiment that can directly probe part of the neutrino oscillation parameter space relevant to solar neutrinos and may also have ^{7}Be neutrino detection capabilities, is now under construction.
• In 1995 there were still reasonable suggestions for nonstandard solar models that could reduce the solar neutrino discrepancy. Today both the increasing precision of helioseismology and the development of solar-model-independent neutrino analyses appear to rule out any such possibility.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.
• Definitive proof of oscillations must be obtained. SNO's ability to distinguish charged and neutral current events is the outstanding opportunity to provide such proof.
• Various oscillation scenarios can account for the data, some of which are quite difficult to distinguish unless low energy solar neutrinos can be measured. Can the U.S. take the lead in developing and mounting one of the several promising experiments to measure the flux and flavor of these neutrinos? Among the proposals discussed by the working group were CLEAN, GaAs, HELLAZ, HERON, LENS, MOON, and Cerenkov-triggered radiochemical detectors employing Cl or I. The ideas range from new technology cryogenic detection schemes to hybrid detectors capable of simultaneously measuring solar neutrino reactions and double beta decay.
• The atmospheric neutrino results are consistent with maximal mixing, an unexpected result given the small mixing angles between quark generations. Can theorists, aided by results from SNO and other new experiments, find a compelling explanation for the pattern of masses and mixing angles?
• Can detectors developed for solar neutrino research probe other neutrino sources: atmospheric neutrinos, geophysical neutrinos, supernova neutrinos, and solar thermal neutrinos?

What are the resources required for this field?
There must be continued strong support for the major experiments now underway. SNO appears to be functioning very well, but the continuation of that experiment through the neutral current phases will require sustained effort. Measuring the heavy-flavor component of the solar neutrino flux is clearly the highest priority. Borexino and KamLAND are tackling the very

challenging problem of active detection of ^{7}Be neutrinos. While Italy and Japan have the lead in these efforts, respectively, the U.S. participation is significant and must be continued.

The principal challenge to U.S. nuclear physics is to assume the lead in developing the next-generation active detector for the lowest energy solar neutrinos. The U.S. currently lacks an effective mechanism for nurturing projects in the R&D phase and for constructing new detectors once the concepts have been proven. This problem is long standing, and has led to lost opportunities such as the gallium experiment. The institutional support available elsewhere - Gran Sasso is the outstanding example – places the U.S. at a disadvantage. Because we lack a facility like Gran Sasso to advocate for the subfield, the community and the funding agencies must be more active in assessing a broad range of developing technologies; in distinguishing promising efforts from others, strongly supporting those R&D directions that make progress; and in mounting major experiments when the development stages have been completed.

Judging from precedents like SNO and Borexino, the typical scale of such major experiments will be in the $25-50M range.

3.2 Neutrino Mass

Single and double beta decay experiments allow one to directly probe neutrino mass. Furthermore, double beta decay experiments test fundamental symmetries and nuclear physics issues.

What scientific questions is this subfield trying to answer?

• Is lepton number conserved? The most sensitive and most direct test of this question is provided by neutrinoless double beta decay.

• How does the neutrino transform under charge conjugation? The neutrino, lacking any additive quantum numbers like electric charge, is unique among the known fermions in having an ambiguous behavior under charge conjugation. It may be its own antiparticle (Majorana) or it may have a distinct antiparticle (Dirac). The possibility of both Majorana and Dirac masses is the key to the seesaw mechanism, the most popular theory explaining why neutrinos are so much lighter than their charged partners.

• What is the nature of neutrino mixing? As a virtual process, neutrinoless double beta decay probes aspects of the neutrino mass matrix that, otherwise, are very difficult to test. It is sensitive not only to light Majorana masses (below 1 eV), but also to heavy ones, above a TeV. The mass derived from double beta decay is sensitive to the relative CP eigenvalues of the mass eigenstates. It is also sensitive to CP-violating phases in the mass matrix.

• How does neutrinoless double beta decay probe new phenomena beyond the Standard Model? Again, as a virtual process, double beta decay is particularly sensitive to new physics, even physics residing at very high energies. Examples include lepton-number-violating right-handed couplings, Majorons, supersymmetry, ...

• What is the absolute scale of neutrino masses? This is the crucial question, yet it cannot be answered by either oscillation experiments, which depend on differences in the squares of the masses, or double beta decay, where eigenstates with different CP eigenvalues interfere. It can be measured in kinematic neutrino mass experiments.

What is the significance of this subfield for nuclear physics and science in general?

• Double beta decay – neutrinoless and two neutrino – is a fundamental nuclear process. It is the only open decay mode for approximately 50 otherwise stable nuclei. It is also the rarest process yet measured in nature. The basic decay process involves a two-nucleon correlation and a nuclear polarizability, and thus is fascinating from the perspective of nuclear structure theory.

• Opportunities to study second-order weak interactions in nature are extremely rare. Double beta decay is one of only two such possibilities in particle physics.

• The question of lepton number violation in the early universe is crucial to cosmology. It is connected, in the standard model, to possible mechanisms for baryogenesis. Early universe lepton number asymmetries can trigger oscillations that distort the neutrino distributions, producing warm – not hot – neutrino dark matter.

• The question of the absolute scale of neutrino masses is crucial to dark matter studies, including interpretations of the cosmic microwave background and large scale structure. Tritium beta decay is a direct test of this mass scale.

• Double beta decay (and solar neutrino) experiments are technologically relevant. Low level counting and ultrapure materials have industrial significance.

What are the achievements of this subfield since the last long range plan?

• Thirty years of effort was required before the allowed process, two-neutrino double beta decay, was observed in 1987. Today accurate lifetimes are known for approximately 12 nuclei.

• Extraordinary efforts to reduce backgrounds has resulted in a "Moore's law" for neutrinoless double beta decay: over the past two decades, lifetime limits have improved by a factor of two every two years. The current limit on the Majorana mass is in the range (0.4-1.0) eV, with the spread reflecting nuclear matrix element uncertainties.

• Double beta decay theory has improved significantly. Shell model methods have been developed to treat the intermediate nuclear Green's function in two-neutrino decay. Full or nearly full fp-shell diagonalizations have been done. Shell model Monte Carlo methods have been developed and checked against exact shell model results.

• Tritium β decay mass limits have reached 2.2 eV (95% c.l.), a bound important to cosmology. The latest results appear to be free of systematic problems.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.

• Radiogenic and cosmogenic backgrounds have been tremendously suppressed by the use of ultrapure materials and by mounting experiments underground. The most challenging background in many cases is now the high-energy tail of the 2ν process, a serious limitation for detectors lacking excellent electron energy resolution. Thus high resolution detectors must be developed.

• The counting rate is a fundamental limit at current ~ 10 kg detector masses. With lifetime limits now above 10^{25} years, the next generation of detectors must employ larger masses (~ 1000 kg).

• The physically relevant scales for 0ν double beta decay experiments are still unclear. Current theoretical models that explain the solar and atmospheric neutrino results with Majorana neutrinos predict a broad range of double beta decay masses (typically from 1 eV to 10^{-5} eV).

• The goal of future direct ν_e mass searches is a sensitivity below 1 eV. The new ideas include the proposed 7m Karlsruhe spectrometer and cryogenic calorimeters using Re.

What are the resources required for this field?
The current generation of neutrinoless double beta decay experiments includes the Heidelberg-Moscow and IGEX experiments on ^{76}Ge, the Caltech-Neuchatel effort on ^{136}Xe, and the ELEGANTS and NEMO-3 ^{100}Mo measurements. They have comparable goals (lifetime limits of $\sim 10^{25}$ years) and isotope masses of $\sim$ 10kg. The Heidelberg-Moscow experiment, which has acquired more than 35 kg-years of data, has set a limit of 2×10^{25} years on the ^{76}Ge lifetime. All of these experiments are being conducted outside the U.S., though several involve U.S. collaborators.

The new large-mass proposals have as their goal Majorana mass limits in the range of 0.03-0.10 eV. This is an important region since the δm^2 deduced by Super-Kamiokande is centered around $\sim (0.05 \text{ eV})^2$. The proposed experiments include CAMEO (^{116}Cd and ^{100}Mo in Borexino's CTF), CUORE (cryogenic detector using ^{130}Te), EXO (a laser tagged TPC using ^{136}Xe), GENIUS and MAJORANA (enriched ^{76}Ge), and MOON (^{100}Mo foils with plastic scintillator), Some of these detectors are becoming well developed, while others require considerable R&D. Some of the proposals, such as EXO, GENIUS, and MAJORANA require Russian isotopic enrichment facilities which are currently available, but may not be so indefinitely.

Among the resources needed are consistent support for R&D in those cases where significant development is necessary; agency help in defining procedures where developed projects can be evaluated and supported; and support for international collaborations (most of the next-generation experiments listed above are international). The anticipated cost of a typical 1000 kg experiment is $\sim$ \$10M, exclusive of isotope enrichment costs (which may be provided by other agencies). There is need for some redundancy in double beta decay studies because of nuclear matrix element uncertainties and because the ultimate sensitivity of new approaches is often difficult to predict.

A U.S. underground site for mounting double beta decay experiments is another issue. While the needs of experiments differ, current experiments typically require about 1700 m.w.e. coverage. Thus near-term requirements can be satisfied by sites like WIPP, but deeper sites will be required by most next-generation detectors.

While shell model treatments of double beta decay have become more sophisticated in the last ten years, fundamental issues still need attention. Probably the most important is the effect of shells in the excluded space: how do these renormalize the shell-model $\beta\beta$ decay operators? Any observation of $0\nu\ \beta\beta$ decay demonstrates lepton number violation, but theory is required to relate lifetimes to neutrino masses.

In tritium β decay near-term activity will focus on the Karlsruhe-Mainz-Troitsk project, an effort to push mass limits to ~ 0.5 eV with a massive 7m spectrometer. The estimated cost is $10-15M. Other groups have been invited to join. Thus support is needed for U.S. collaborators wanting to help in this effort. There are also interesting cryogenic Re calorimeters under development in Genova and Milano. On the longer term, severe obstacles will have to be overcome to further increase sensitivities to ~ 0.1 eV. Molecular excited state contributions are one of the troublesome issues at this level.

3.3 Supernova Physics

Nuclear physics interests focus on realistic modeling of core-collapse supernovae, understanding the associated nucleosynthesis, and building and operating neutrino observatories to measure the flux and flavors of neutrinos from the next galactic supernova.

What scientific questions is this subfield trying to answer?

- What is the mechanism by which a core-collapse supernova ejects its mantle? Can we build a quantitative standard model of the explosion, including neutrino production and associated nucleosynthesis, such as the r-process and the neutrino process?
- What experiments can be done to test such a standard model? Can we use the nucleosynthesis, particularly the pattern of r-process metals, to diagnose the explosion, in analogy with the use of d, ^{3,4}He, and ^{6,7}Li to test the big bang? Can we use the neutrino flux from the next galactic supernova to learn about the explosion mechanism and, possibly, to probe properties of the protoneutron star? Can we measure the gravitational wave signal in LIGO, and supernova gamma rays in INTEGRAL?
- Can we exploit supernovae to search for new phenomena, including neutrino oscillations and neutrino masses? As the neutrinosphere resides at a density $\sim 10^{12}$ g/cm^3, supernovae allow us to extend our tests of matter effects on oscillations by 10 orders of magnitude.

What is the significance of this subfield for nuclear physics and science in general?

• The supernova mechanism is one of the outstanding challenges in nuclear theory and theoretical astrophysics, involving an extraordinary range of physics – laboratory nuclear astrophysics, stellar evolution, neutrino interactions, and the behavior of bulk nuclear matter at extreme densities and temperatures.
• Supernovae are thought to have produced about half of the heavy nuclei found in nature. Nucleosynthesis is a central question for nuclear physics.
• To the extent that we can understand such synthesis, we can predict, given a galactic model, how metallicities evolve, an important issue in astronomical abundance determinations and gamma ray astronomy.
• Neutron stars are the only example in nature of the nuclear theorist's test case, bulk nuclear matter. It is very likely that new phenomena – mixed or quark-matter phases, color superconductivity, kaon condensation – exist at neutron star densities. In the next decade precise mass/radii determinations are likely to be made. This will provide a crucial check on our theories of the equation of state of dense nuclear matter.
• Core collapse supernovae (and neutron star merges) may produce detectable gravitational radiation. Accurate modeling of the collapse could help LIGO experimentalists by defining the wave forms that they must find.
• Supernova neutrino detection is a key part of the "supernova watch" program that also involves gravitational wave detectors and optical observatories.
• Supernova modeling is a terascale (and beyond) "grand challenge" problem that requires collaboration between nuclear theorists, astrophysicists, and computer scientists. Many of the underlying issues, such as radiation transport, hydrodynamics, shock wave propagation, and the mathematical challenge of scalable algorithms for large, sparse, linear systems, are common to problems ranging from medical imaging to climate prediction to internal combustion. Thus the developments from supernova models will benefit many other sciences.

What are the achievements of this subfield since the last long range plan?
• At the time of supernova 1987A, two neutrino detectors were operational and ~ 18 events were recorded. Today there are four operating detectors and three others that should be operational in the next 1-2 years. Approximately 10^4 neutrinos should be detected at the time of the next galactic supernova.
• The first semi-realistic two-dimensional simulations of supernova explosions

have been performed. This could be an important step in understanding the mixing apparent in the ejecta of observed supernovae.

• Full Boltzmann neutrino transport has been implemented in one dimensional models.

• Significant progress has been made in descriptions of the progenitor, e.g., multi-D models that account for convection and rotation. Improved electron capture and beta decay rates and improved neutrino opacities have made the input microphysics much more realistic.

• Progress has been made in modeling the r-process, including improved weak interaction rates, a better understanding of the effects of mass formula uncertainties and phenomena such as the vanishing of shell closures, and inclusion of neutrino postprocessing effects.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.

• The key challenge is to develop a supernova standard model that incorporates realistic neutrino transport and microphysics. Current 1D models generally fail to explode. This could reflect some flaw in our understanding of the physics, or the importance of doing multi-D simulations.

• Test relevant microphysics input into supernova simulations, such as mass formulas used in r-process synthesis and neutrino-nucleus cross sections important to opacities and nucleosynthesis, by direct laboratory measurements at RIA, ORLaND, and other facilities.

• Test supernova models by comparing predicted supernova neutrino flavor, energy, and time distributions to measurements made in underground neutrino detectors.

• Exploit the next galactic supernova to make kinematic tests of neutrino masses.

• Exploit the next galactic supernova to search for the MSW flavor transformation $\nu_\tau \rightarrow \nu_e$. Because supernova ν_e's are more strongly coupled to the matter, they are predicted to be substantially less energetic than the heavy flavor neutrinos. MSW oscillations would produce a distinctive spectral inversion, distorting the angular distribution of events detected in SNO and Super-Kamiokande.

• A variety of physics – neutrino heating, convection, rotation, magnetic fields, general relativity – are inadequately modeled in current multi-D simulations. It is not known which of these effects may be essential to successful explosions. Nor is it clear how dependent (or independent) explosions may be on the class of progenitor star.

What are the resources required for this field?
A fundamental difficulty is the low rate of galactic supernovae, estimated to be $\sim 1/30$ years. This corresponds to a timescale that exceeds some (though not all) neutrino detector lifetimes. The challenge, then, is to begin to view neutrino detectors as observatories, rather than experiments. Compromises may be required because highly instrumented, high maintenance detectors become more costly, both in dollars and in the human investment, when operated over decades.

When possible, it is clearly preferable to exploit detectors built for other purposes – Super-Kamiokande, SNO, BOREXINO, or a next-generation proton decay detector like UNO – as supernova observatories. This allows the physicists involved with the detector to do other physics while waiting for a rare supernova. Yet there are proposals for dedicated experiments, such as OMNIS, that are designed to minimize manpower requirements.

If supernova observatories are exclusively multipurpose detectors, then in some sense they monitor the galaxy for free. But it is essential that detectors with the requisite capabilities monitor the galaxy at all times, to avoid missing a once-in-a-lifetime opportunity. This is a theme of the supernova watch. In the case of SN1987A, we measured supernova $\bar{\nu}_e$'s. The goal, at the time of the next supernova, should be to measure separately the properties of the ν_e, $\bar{\nu}_e$, and heavy flavor fluxes. Clearly the nuclear physics community needs to be highly involved in supernova watch plans. Decisions to turn off detectors must take into consideration whether supernova capabilities are being lost. This also applies to scheduled maintenance.

The arguments for a theory initiative in supernova physics are very strong. This modeling is central not only to neutrino physics, but also to other major nuclear physics initiatives, such as RIA. The development of multi-D models with realistic neutrino transport and microphysics is possible at this time. Presuming that terascale machines are made available, the primary resource needed is person power: the groups currently involved in supernova theory are greatly understaffed. A reasonable starting budget for such an initiative is \$2.0M/year, most of which should be invested in young scientists who would attack the neutrino transport, hydrodynamics, and computer science issues associated with supernova modeling, as well as critical issues involving the underlying microphysics, such as the nuclear structure important to neutrino-nucleus scattering and other weak interactions, the nuclear equation of state at high density, and neutrino opacities.

3.4 Underground Laboratories

What scientific questions is this subfield trying to answer?
• What type of environment, isolated from both cosmic ray and natural radioactivity backgrounds, can be provided to optimize the success of future background-sensitive experiments?
• What scientific opportunities might be realized if a dedicated deep underground facility were available?

What is the significance of this subfield for nuclear physics and science in general?
• Despite early leadership in the field of underground science, the U.S. has fallen behind Canada, Europe, and Japan in providing dedicated facilities for such experiments.
• The shortage of suitable underground facilities is a critical concern for next generation neutrino, proton decay, and dark matter experiments.

What are the achievements of this subfield since the last long range plan?
• SNO has been constructed and has surpassed its background specifications, demonstrating that a clean-room environment can be maintained at great depth, even in an active mine.
• WIPP, the dedicated waste isolation facility in New Mexico, has offered to host scientific experiments. This provides a U.S. laboratory site at moderate depth ($\sim$ 2000 m.w.e.). Because it is located in a salt formation, U and Th background levels are low.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.
• There are outstanding opportunities to create a deep underground national laboratory that will serve the next generation of solar neutrino, double beta decay, dark matter, atmospheric neutrino, and proton decay experiments. Deep sites are also important to accelerator measurements of astrophysical S-factors, and potentially interesting for other sciences and industry.

The model for such a national laboratory is Gran Sasso, located at an average depth of 4300 m.w.e. and with horizontal access off a highway excavated through the Gran Sasso d'Italia. The laboratory has been in existence since the early 1980's. The competition for space is keen. The laboratory currently hosts a broad program of experiments: the GNO successor to the GALLEX solar neutrino experiment; Borexino; the dark matter search DAMA; the Heidelberg-Moscow ^{76}Ge double beta decay experiment; the EASTOP air shower array for cosmic ray physics (and for coincidence with underground detectors), located on top of the mountain; the ICARUS liquid Ar detector; LVD, a 1.6 kton liquid scintillator detector; MACRO, a large monopole detector; and LUNA, a low-energy accelerator for nuclear astrophysics.

The Kamioka laboratory, located in a mine in the Japanese alps, is also becoming a multipurpose facility. Activities include Super-Kamiokande, KamLAND, a gravity wave detector under construction, and double beta decay.

There has been serious discussion in the U.S. of a deep underground national laboratory since the early 1980s. The question has become very urgent with the announcement that the Homestake Mine, in South Dakota, will close in 16 months. Homestake is a deep, hardrock mine with a large shaft (15 $\times$ 20 ft) running to 4850 ft; additional levels exist every 150 ft, to 8000 ft. The State of South Dakota, in combination with the South Dakota School of Mines, has expressed interest in taking on the operations, management, and liability burdens that would be associated with an underground laboratory. The mine has considerable infrastructure (pumps, power, air exhaust systems, multiple shafts). But significant investments are needed to produce an above-ground campus comparable to that at Gran Sasso; to install modern lifts that utilize the full dimensions of the shafts; to produce large halls of the type existing at Gran Sasso; and to engineer areas for cryogenics and other facilities where safety is a concern.

There is also a proposal for constructing a horizontal access laboratory by tunneling beneath Mt. San Jacinto, near Palm Springs. A laboratory located at the end of a 2.5 mile tunnel would provide 6000 ft of rock overbunden. Although this requires construction of a laboratory and its infrastructure from scratch, the plan offers the advantages of horizontal access and proximity to a number of physics laboratories in California.

These possibilities for deep sites, together with the existing shallower sites at the Soudan Mine and WIPP, should be the starting point for a community discussion of how to prepare for the next generation of underground experiments. These sites have complementary aspects: different radioactivities, access, depth potentials, etc. The community has an opportunity to consider which facility or combination of facilities will help the next generation of experiments reach their potential. As Gran Sasso has proved, both the underground site and the supporting infrastructure are important in facilitating new experiments.

What are the resources required for this field?
The creation of a national deep underground laboratory is a major investment, the largest discussed in this report. In the case of Homestake, there is a large investment already made by the miners: the value of the existing mile-long 15 $\times$ 20 ft shaft is considerably in excess of \$50M. The additional investment that will be needed from scientific agencies to convert Homestake into a suitable national facility may be smaller, but is still significant. The costs include improved lifts, the experimental halls, and the above-ground facilities of the type provided by Gran Sasso. The cost of the experimental program of such a facility, extrapolating from Gran Sasso, is likely in the \$10-25M/year range. There are important efficiencies in such a laboratory because experiments can make use of a common infrastructure.

The construction costs of an ab initio laboratory like San Jacinto are more difficult to estimate. A reasonable extrapolation of the estimates made in the early 1980s, when the proposal was first discussed, yields $\sim$ \$100M.

It is unlikely that the use of such a laboratory would be confined to nuclear and particle physics: isolated environments are also of interest to geophysicists, the electronics industry, biologists, and gravity wave experimentalists.

3.5 Reactor and Accelerator Neutrinos

What scientific questions is this subfield trying to answer?
- What can be learned about neutrino properties from controlled, terrestrial source measurements?
- What is the strangeness content of the nucleon?
- Is our understanding of neutrino-nucleus cross sections important to supernovae and the solar neutrino problem correct?

What is the significance of this subfield for nuclear physics and for science *in general?*

• Even with strong evidence for neutrino oscillations from atmospheric and solar neutrino studies, the underlying physics issues are so important that confirmation of oscillations in the laboratory is crucial. The use of known neutrino sources and the ability to adjust the source-target distance are among the advantages of accelerator and reactor neutrinos. Disappearance and appearance measurements can be made.

• Neutrinos are potentially interesting as probes of strangeness in the nucleon and nucleus, with simpler radiative corrections.

• There are very few quantitative tests of the accuracy of calculated neutrino-nucleus cross sections. The renormalization of the effective shell model axial vector coupling g_A is known from β decay, while muon capture probes first-forbidden weak responses for time-like four-momenta. But apart from these constraints, most of the nuclear physics used in describing supernova neutrino-nucleus cross sections (space-like four-momentum transfers, important allowed and first forbidden transitions) has not been subjected to detailed experimental tests. Yet many aspects of supernova physics, including nucleosynthesis, require accurate cross sections.

What are the achievements of this subfield since the last long range plan?

• LSND was completed in 1998, and KARMEN II has reported three years of data (2/97-3/00). Evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ has been found in the LSND experiment. KARMEN has found no evidence for oscillations, though a portion of the LSND allowed range, corresponding to small mixing angles and masses, is not ruled out.

• The Chooz and Palo Verde reactor $\bar{\nu}_e$ oscillation experiments constrained δm^2 to below 10^{-3} eV^2 in the disappearance channel at maximum mixing angle. This became an important constraint on the interpretation of the Super-Kamiokande atmospheric neutrino results.

• Early results from the K2K long-baseline oscillation experiment disfavor the no oscillation hypothesis at about the two standard deviation level. This is the first hint that the Super-Kamiokande atmospheric neutrino results may have laboratory confirmation.

• LSND and KARMEN obtained ^{12}C exclusive charge current cross sections for exciting the ground state of ^{12}N. The results are in good agreement with theory. Inclusive charge current cross sections were also obtained. KARMEN measured neutral current neutrino excitation of the 15.11 MeV state in ^{12}C.

These results are the first obtained for complex nuclei.
• Fermilab's MiniBooNE, the followup experiment to LSND, and KamLAND a reactor antineutrino experiment are under construction.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.
• The completion of MiniBooNE is important. If both the atmospheric and solar neutrino problems are attributed to neutrino oscillations, and if the LSND results are correct, then a good fit to the data can only be obtained by hypothesizing a fourth light neutrino with sterile interactions. Thus confirming or ruling out the LSND results has important consequences for interpretations of the neutrino data. If the LSND results are confirmed by MiniBooNE, it will be important to build a second detector at a different distance in order to define the oscillation parameters precisely.
• The KamLAND reactor antineutrino experiment has the potential to be the first laboratory experiment to probe δm^2 values directly relevant to the solar neutrino problem. The projected sensitivity covers all of the large mixing angle solar neutrino solution. Thus completion of this experiment is a high priority for nuclear physics.
• The Spallation Neutron Source (SNS) now under construction at Oak Ridge will produce an intense source of neutrinos with a pulsed time structure (similar to that of ISIS/KARMEN) and with a very favorable $\bar{\nu}_e/\bar{\nu}_\mu \sim 3 \times 10^{-4}$ ratio. This will be the most intense, pulsed, intermediate energy neutrino source available. An interesting program of possible experiments has been proposed, some of which exploit the similarities between the SNS neutrino spectrum and that from a supernova. The opportunity to build a neutrino hall – a shielded room in which experiments can be mounted – should be seized. It is important to situate the room as close as possible to the SNS mercury beam stop. This facility (ORLaND) will stimulate the community to propose detectors and experiments: the possibilities include oscillation experiments, searches for isoscalar axial charge transitions, and the continuation of the neutrino-nucleus cross section program begun by KARMEN and LSND.
• The completion of the K2K experiment is important. Laboratory confirmation of the Super-Kamiokande results would have great impact on the field.
• Much of the underlying physics of ORLaND, the supernova mechanism, and other problems discussed here involve nuclear structure theory. The U.S. nu-

clear theory program is currently quite weak in this area. Neutrino physics has strong student appeal and, because it involves many nuclear structure issues, provides an opportunity for training students in an area of some national importance.

What are the resources required for this field?
It is important to continue nuclear physics support for the MiniBooNE and KamLAND efforts. These experiments focus directly on issues of importance to nuclear physics: checking the LSND claims and probing neutrino oscillation parameters relevant to the solar neutrino problem.

The SNS neutrino hall requires a significant investment, perhaps $15M. The additional cost of detectors for the experimental program has been estimated to be $\sim$ $45M.

3.6 Dark Matter Atmospheric Neutrinos, and High Energy Neutrinos

What scientific questions is this subfield trying to answer?
• Dark matter is evident from its gravitation effects. What is its composition?
• What can be learned by extending the program of astrophysical neutrino detection to higher energies? In analogy with solar neutrinos and supernova neutrinos, could such a program allow us to probe the structure of active galactic nuclei and other high-energy objects?
• What contributions can nuclear physics make to clarifying the atmospheric neutrino problem?

What is the significance of this subfield for nuclear physics and science in general?
• Many phenomena in astrophysics – such as 10^{21} eV cosmic rays and gamma ray bursts corresponding to isotropic sources of energy 10^{53} ergs – involve extraordinary scales of energy and particle acceleration. Even in our own galaxy there are hints, from AGASA, of 10^{18} eV events. The detection of neutrinos produced by such natural accelerators might help us understand the acceleration mechanism and pinpoint the source. Nuclear physics can contribute to such high-energy astrophysics questions because of our interest

in water Cerenkov and other neutrino detection schemes.
• Dark mater research has profound implications to not only cosmological questions, but also to current models of extra dimensions and string theories.

What are the achievements of this subfield since the last long range plan?
• Super-Kamiokande has measured with very good statistics a distinctive zenith angle dependence in the ratio of electron to muon events from atmospheric neutrinos. Most experts accept this result as the first demonstration of physics (nonzero neutrino masses, flavor mixing) beyond the Standard Model.
• AMANDA, the high-energy neutrino detector located 1500-2000m below the surface of the Antarctic ice sheet, was commissioned in February, 1997. The experimentalists have observed atmospheric neutrinos and are searching for astronomical sources.
• Dark Matter searches continue to improve sensitivity. Construction of CDMS-II is currently underway at Soudan and a major upgrade of the successful MIT RF cavity axion search is also in progress.
• Experiments supported by nuclear physics have tested gravity at short, sub-mm distances. These results constrain some proposed string theories that predict extra dimensions.

What are the theoretical and experimental challenges facing the field? Identify the new opportunities.

• The successful commissioning of AMANDA opens up the possibility of large Antarctic arrays to do high energy neutrino astronomy. AMANDA has given the U.S. leadership in this area. The next generation detector, ICECUBE, is designed to map the neutrino sky from GeV to PeV energies, determining both the diffuse flux from galactic and extra-galactic sources and point sources, such as active galactic nuclei or gamma ray bursters. High energy neutrinos are unique tracers of high energy protons and nuclei that we know are accelerated to extraordinary energies somewhere in the cosmos. The behavior of nuclei at very high energies and their interactions with the interstellar medium are topics of interest to nuclear physicists.
• Some double beta decay experiments, such as MAJORANA, have potential sensitivity to dark matter. Efforts should be made to exploit these abilities.

What are the resources required for this field?
Studies of subatomic matter do not always fit within the conventional definitions of nuclear or particle physics. Yet the physics is compelling and often the work is being done by physicists being funded from nuclear physics grants. It is important that both the community and agencies recognize and support such investigations. An effort should be made to facilitate the funding of such research.

3.7 Theory Efforts

Two of the long range plan initiatives now under consideration – the neutrino program outlined here and the Rare Isotope Accelerator – have important links to nuclear structure theory. There are very few U.S. nuclear structure theorists of age $\lesssim 40$ years occupying tenure track university or national laboratory positions. (Interestingly, those few all seem to have close connections to weak interactions and neutrino physics, particularly neutrino astrophysics.) It is important, for the success of the experimental part of the LRP program, to enhance the nuclear theory program in the relevant areas of nuclear structure and nuclear astrophysics. The creation of 20 entry-level university nuclear theory/nuclear astrophysics positions over a period of 5 to 10 years would require an increase in the theory budget of about $3M/year. This $3M investment could be used initially to fund tenure-track bridge positions, then gradually rolled over to provide continuing research support (summer salary, graduate students, and postdocs) once the bridges are completed.

The importance of additional theory effort on the core-collapse supernova mechanism was discussed in Section 3.3.

4 Fundamental Symmetries Subfield Summaries

In what follows, we summarize the important developments that have occurred in fundamental symmetry tests in nuclear physics since the last Long Range Plan and survey the opportunities for the next five years. The physics addressed here falls under one or both of the following primary scientific aims of the field:

(1) precision searches for new electroweak physics exploiting techniques at low-energies;

(2) the use of the weak interaction to study novel aspects of hadronic and nuclear structure.

Significant developments aimed at addressing both of these principle scientific questions have occurred over the past five years which put the field on the threshold of a new era of high-impact physics. While these developments are discussed in detail below, we mention a few of them here. From an experimental standpoint, one has witnessed the development of new techniques with cold and ultracold neutrons, the successful measurement of parity-violating asymmetries with polarized electrons at parts in 10^7, a test of the Standard Model (SM) at the 4ppm level with a new measurement of the muon anomalous magnetic moment, and the development of new atomic physics techniques aimed at studying parity and or time-reversal violating properties of nuclei. Theoretically, the field has also seen important progress, including the application of effective field theory to a variety of electroweak observables, the further development of Green's Function Monte Carlo methods as applied to weak processes, and progress in lattice QCD which open up new possibilities for first principles QCD calculations of hadronic weak matrix elements. Nevertheless, there exist a number of important, open theoretical issues whose resolution is critical to the successful interpretation of future experimental studies. Addressing the theoretical manpower shortage, as well as the funding of new experimental initiatives, constitutes one of the priorities of the field.

The experimental programs described below utilize a wide range of facilities from table-top setups to high-energy accelerators. On-going and proposed measurements involving neutrons represent a significant fraction of the overall program. Access in the U.S. to cold and ultracold neutron beams is presently limited to NIST and LANSCE. The addition of a cold neutron beam end station to the SNS at Oak Ridge National Laboraty, which is estimated to cost approximately \$3M, would greatly enhance the access to these beams. A UCN facility will ultimately be needed in order to carry out the full program of fundamental studies with neutrons. Development work aimed toward the construction of a dedicated UCN facility is now taking place. Present estimates for constructing the facility are \$10-15M. These costs represent those for beam lines and not the experiments.

For the sake of organization, we have grouped the components of low-energy electroweak studies into six broad categories. The two overriding physics issues for this subfield are common to the topics described below, only the techniques used to probe the physics differ. Consequently the format for this section differs from that of the previous section where the topics that were discussed had somewhat different physics goals. This subfield has close ties to neutrino physics, astrophysics and cosmology, high-energy physics and atomic physics. Certainly any low energy symmetry tests that uncover a deviation from SM predictions will have a *profound* influence on all of these fields.

4.1 Time-Reversal Tests

Advances in neutron beam technology, as well as in techniques involving atom trapping, have paved the way for significant improvements in the precision that can be obtained in searches for permanent electric dipole moments (EDM's) of the neutron, electron, and neutral atoms. Improvements by several orders of magnitude appear feasible on a timescale of five to ten years. In particular

- The current limit on the neutron EDM of $|d_n| < 8 \times 10^{-26}$ e-cm could be improved by two to four orders of magnitude using new UCN technology.

- A factor of four improvement in the limit on the EDM of ^{199}Hg has recently been reported by the Seattle group, and an additional factor of two improvement may be possible with current technology. In addition, developments with radioactive atoms such as ^{225}Rn and ^{223}Ra may provide new probes of T-violation with advanced sensitivity.

- By exploiting enhanced internal molecular electric fields in PbO molecules, the Yale-Amherst collaboration hopes to achieve a two to four order of magnitude improvement on the current electron EDM limit $|d_e| < 4 \times 10^{-27}$ e-cm.

The predictions of the SM, based on the parameters of the CKM matrix and the observation of CP-violation in neutral K decays, are well beyond what even these improved studies might access. SM predictions for the neutron

EDM, for example, vary in the $10^{-30} - 10^{-32}$ e-cm range. However, a number of new physics scenarios, such as sypersymmetric grand unified theories, left-right symmetric models, etc, predict EDM's large enough to be seen by these prospective measurements. Moreover, the observed baryon asymmetry of the universe and standard big bang nucleosynthesis imply the existence of additional sources of CP-violation beyond that of the SM. The prospective EDM studies would have a significant impact on our understanding of non-SM sources of CP violation.

The complementarity of neutron, electron, and neutral atom EDM measurements also merits emphasis. While d_e is insensitive to non-leptonic CP-violation, such as the θ-term in the QCD Lagrangian, neutron and neutral atom EDM's provide powerful probes of such interactions. Similarly, in a more exotic scenario, $|d_e|$ provides the most stringent constraints on new T-violating P-conserving interactions when parity-symmetry is restored at short distances. In contrast, the bounds from the EDM's of neutral atoms, such as ^{199}Hg, are considerably weaker. More generally, in order to sort out among competing models for new CP-violation in the light quark and lepton sector, one requires input from all three types of EDM measurements.

A complementary approach to the search for non-SM CP-violation is the measurement of time-reversal violating, parity-conserving (TVPC) observables. In comparison to EDM's, direct TVPC observables probe new sources of parity-conserving C-violation (and, thus, CP-violation) under scenarios where C is broken at a scale below the breaking of left-right symmetry breaking. There exist a number of future possibilities for performing such direct searches:

- Recently, the emiT collaboration has improved the limits on the TVPC D-correlation in neutron β-decay. The experiment implies $|D| \lesssim 0.5 \times 10^{-3}$. Further improvements are expected at NIST. From the standpoint of theoretical intepretability, one expects final state effects to enter at the 10^{-5} level. New efforts to improve the reliability of theoretical final state effects calculations are warranted.

- A measurement of the TVPC effects in $\vec{p}d$ scattering is being developed at COSY, and the possibility of searching for TVPC, charge symmetry breaking correlations in np elastic scattering at TRIUMF is under consideration.

- Precise measurements of the TVPC five-fold correlation in polarized epithermal neutral transmission through aligned heavy nuclei have been performed by a group at TUNL. Improvements in precision for this observable are possible with a pulsed neutron beam at the SNS.

4.2 β-Decay Correlations and CKM Unitarity

Nuclear physics provides the most stringent test of the unitarity of the Cabibbo-Kobayashi-Maskawa matrix via determinations of V_{ud} and V_{us}. As analyzed by the Particle Data Group, the value of V_{ud} extracted from superallowed nuclear Fermi β-decay, when combined with the 30 year-old value of V_{us} extracted from Ke_3 decays, suggests a $\gtrsim$ 2.2 σ deviation from unitarity. If this deviation persists after further tests, it would signal the presence of new physics. Possible sources include right-handed gauge bosons, leptoquarks, and new $B-L$ violating interactions in SUSY. The β-decay probes of these new physics scenarios complement those obtained at colliders. In the case of left-right symmetric theories, for example, the latest Tevatron results imply lower bounds on M_{W_R} in the 800-900 GeV range. These bounds are fairly insensitive to the left-right sector mixing angle. The β-decay vector current observables, in contrast, provide the most powerful probe of the mixing angle. Similarly, when β-decay V_{ud} results are combined with those for the $\pi^+ \to e^+\nu_e$ to $\pi^+ \to \mu^+\nu_\mu$ ratio and for cesium atomic PV, one obtains the most powerful constraints on new $B-L$ violating light quark interactions in SUSY. The constraints from relevant high-energy data – primarly for the W-mass, $\sin^2\theta_W$, and various rare decays – are weaker that those derived from combined low-energy results.

Until recently, efforts to extract V_{ud} from neutron β asymmetries have not reached the precision obtained in superallowed nuclear β decay. Moreover, there have existed considerable differences between various measurements of the neutron β-asymmetry parameter, A. However, the PERKEO collaboration at ILL has performed a new measurement of A at the few parts per thousand level. The measurement represents a significant improvement over past studies, in that corrections applied to the raw asymmetry are smaller than the quoted systematic uncertainty. In light of the past discrepancies among neutron measurements, it is important that a separate determination of A be made with similar precision. The advances in cold and ultracold neutron beam technology open up important possibilities for doing so. In addition the parity conserving electron-neutrino correlation in neutron β decay can be used to measure the correlation coefficient a which is also sensitive to g_A/g_V.

There exist a variety of fronts on which new efforts should be undertaken to test CKM unitarity:

- Improved measurements of the neutron β decay correlations, in combination with a more precise value for the neutron lifetime, would provide a determination of V_{ud} free from possible nuclear structure effects. The improved neutron measurements would become possible if the new cold and ultracold neutron beam facilities are realized.

- Calculations of the nuclear structure-dependent corrections δ_C and Δ_R, which enter the extraction of V_{ud} from superallowed Fermi nuclear β-decay, should be further tested and improved.

- A new measurement of V_{us} in K_{e3} decays should be performed. A proposal to do so has been approved at Brookhaven. Funding to operate the facility for this measurement remains to be allocated.

- If the precision can be improved to the level of the neutron and nuclear decay measurements, a measurement of the π β-decay branching ratio would provide an independent, theoretically clean determination of V_{ud}.

In addition to these studies, possibilities exist to improve limits on non $V-A$ interactions. Recent results utilizing $e^+\nu$ correlations indicate that these experiments are nearing the sensitivity needed to uncover new physics. Techniques developed to handle radioactive species – radioactive beams, ion and atom traps – have opened possibilities for significant improvements in precision that could allow observation of G-parity violation originating from charge symmetry breaking due to the difference between the u and d quark masses, or scalar and tensor currents, which are predicted in many extensions of the SM that include charged Higgs bosons or lepto-quarks.

4.3 Parity-violation and the Weak Charge

The weak charges of the electron, proton, and neutral atoms constitute the fundamental vector current coupling of the Z^0 to first generation leptons and quarks at zero momentum transfer. These charges can be computed precisely in the SM so deviations from the predictions would indicate the presence of new physics. Recently, the Boulder group has completed a measurement of the ^{133}Cs weak charge using atomic parity-violation (PV). The experimental precision achieved in that measurement is $\sim 0.3\%$, making the dominant error source atomic theory. With a combined precision on the order of one percent or better, the cesium measurement probes new neutral current interactions in the 1-20 TeV range. Opportunities for additional and complementary weak charge measurements exist during the next Long Range Plan time frame:

- An experiment to measure the weak charge of the electron – using PV Möller scattering – is underway at SLAC. The collaboration hopes to measure the PV asymmetry to 7% accuracy. Given the $1 - 4\sin^2\theta_W$ suppression of the tree-level Möller asymmetry, the measurement would probe new purely leptonic neutral current interactions with the same sensitivity as the cesium atomic PV measurement.

- A collaboration has formed to measure the proton weak charge using PV electron-proton scattering at JLab. Like the Möller asymmetry, the PV $\vec{e}p$ asymmetry is suppressed at forward angles by the $1 - 4\sin^2\theta_W$ tree-level SM weak charge of the proton. While the cesium weak charge is dominated by the contribution from neutrons, the PV $\vec{e}p$ measurement would search for new neutral current physics involving protons, thereby allowing one to perform an isospin filter of new neutral current physics in the light quark and lepton sector. The sensitivity to new physics would be commensurate with that of the cesium atomic PV measurement and would be free of atomic structure complications. The experiment would employ a modification of the G0 magnet planned for use in strange quark searches, and its interpretability relies on the completion of the approved strange quark program at JLab.

The precision of these measurements makes them sensitive to new physics in the 1-20 TeV range and, thus, competitive with high-energy searches for new neutral current physics through the end of the decade. As in the case of the EDM's, we emphasize the complementarity of the atomic, proton, and electron weak charge measurements. Completion of all three is essential. For example, the weak charge of the electron is sensitive to new neutral gauge bosons, but not to leptoquark interactions which arise naturally in SUSY. The latter can be accessed with the semileptonic measurements.

Here, we note an important, open theoretical problem. The major limitation on the extraction of the nuclear weak charge from atomic PV is atomic theory uncertainty. A new theoretical effort to reduce this uncertainty is needed. Alternatively, atomic theory uncertainties can be evaded by measuring weak charges for different isotopes. The ratios of the results are essentially insensitive to new physics on the neutron weak charge and are dominated by possible new physics on the proton weak charge. However, they also carry strong dependence on changes in the neutron distribution along the isotope chain. At present, nuclear theory cannot compute these isotope variations with sufficient precision to make new physics searches feasible with atomic PV isotope ratios. The situation may be helped by a PV electron scattering measurement at JLab:

- An experiment has recently been approved for Hall A to measure the PV asymmetry for elastic scattering from ^{208}Pb. This measurement would provide the most precise determination of the neutron distribution of a heavy nucleus. It may also provide an experimental "calibration" of the nuclear structure theory for neutron distributions in heavy nuclei, thereby allowing one to reduce the nuclear theory uncertainty entering the interpretation of atomic PV isotope ratio studies. The extent to which the latter possibility is feasible remains to be fully explored.

4.4 Muon Physics

Muon physics features a rich and diverse program in precision measurements of fundamental importance. Most significantly, a new measurement of the muon anomalous magnetic moment, with an uncertainty of 1.3 ppm, has been completed at the BNL muon storage ring. The result differs from the Standard Model prediction by 2.6σ. If the difference cannot be accounted for by hadronic loop effects, the most likely explanation is the presence of supersymmetric loop contributions. Analysis of additional data should reduce the quoted experimental uncertainty by a factor of two. Muonium atom studies at Los Alamos improved the magnetic moment ratio μ_μ/μ_p precision to better than 120 ppb which led to new stringent limits on the muonium-antimuonium conversion process and on the deviation from unity of the muon to electron charge ratio. The MEGA experiment reported its final result on the lepton flavor violation reaction $\mu^+ \to e^+\gamma$ at less than 1.2×10^{-11} (90% C.L.). At TRIUMF, the radiative muon capture (RMC) experiment measured the induced pseudoscalar coupling constant, g_p, and found a value more than four standard deviations larger than expected from chiral pertubation theory.

New and exciting projects have also been developed during this period which will be realized during the next 3 - 10 years. Some of those with significant U.S. leadership or participation include:

- μLan at PSI: A new measurement of the positive muon lifetime with the goal of a 20-fold improvement in precision will lead to a determination of the Fermi coupling constant, G_F, to better than 1 ppm. For this effort, a high-intensity muon beam at PSI will be instrumented with a "kicker" in order to produce an artifically time-structured, high-repetition-rate, pulsed muon source. The development is expected to be useful for other followup experiments.

- $\mu Capture$ at PSI: A new (ordinary) muon capture experiment featuring a novel high-pressure, high-purity hydrogen TPC. The lifetime difference $(\tau_{\mu^+} - \tau_{\mu^-})$ determines the capture rate. The use of H_2 gas rather than liquid will, for the first time, avoid the interpretation dependence of the result on poorly known molecular physics.

- $\mu^- p$ Lamb Shift at PSI: Intense low-energy muon beams have enabled a measurement of the muonic Lamb shift in low-pressure H_2 gas to an estimated precision of 30 ppm. At this level, the proton rms charge radius would be inferred at the 0.1% level, a significant advance. The motivation for such an improvement is coupled to continually improved H Lamb shift QED tests which are presently limited by the proton finite size correction uncertainty.

- TWIST at TRIUMF: This new effort will improve the Michel parameters by factors of 25 to 60 and improve knowledge of the couplings by 3 - 10. Such constraints severely restrict SM extensions to the weak interaction. For example in a manifest $L - R$ symmetric model, these limits correspond to a right-handed W mass greater than 700 GeV and a reduction of the mixing angle to $\zeta < 0.01$.

4.5 Baryon and Lepton Number Violation

The conservation of $B-L$ is an accidental symmetry of the Standard Model which need not persist in SM extensions. There exist, for example, simple extensions of the minimal supersymmetric SM which include new $B-L$ violating interactions. Experiments provide constraints on some, but not all, of these so-called R-parity violating effects. Among the most stringent is the search for proton decay. Despite these limits, however, it is known that some form of B violation must have occured in the early universe in order to produce the observed baryon asymmetry of the universe. It is thus of interest to look for direct signatures of B violation. In addition, some scenarios for this baryon asymmetry provide for B violation indirectly through the presence of a Majorana neutrino, whose L violating properties may generate B violation in $B-L$ conserving models.

Apart from the search for proton decay, there exist two additional directions for B and L violation searches of interest to nuclear physics:

- MECO at BNL: A new $\mu^- N \to e^- N$ conversion experiment aimed at a sensitivity of better than 2×10^{-17} branching fraction is being launched at BNL. This grand effort will probe most of the the SUSY-GUT parameter space and it will challenge SM extensions with mass scales at the 1000's of GeV equivalent level. The project is being considered for funding by the NSF Major Research Experiment program.

- A search for $n-\bar{n}$ oscillations using an intense neutron source at the HFIR facility at Oak Ridge. The existence of such oscillations requires $\Delta B = 2$. In $B-L$ nonconserving theories such as left-right symmetric models, the existence of Majorana neutrinos, whose interactions involve $\Delta L = 2$, could be linked to the occurence of $\Delta B = 2$ processes. The recent observation of neutrino oscillations, thus, strengthens the motivation for performing $n-\bar{n}$ searches. The present limits on intranuclear neutron-antineutron transitions is slightly below 10^{32} years. A new search using the high neutron flux at the HFIR facility at Oak

Ridge, could improve this limit by three orders of magnitude, making it commensurate with proton decay limits. Supporting the development of such a measurement would be a worthwhile investment.

4.6 Parity violation and Hadronic/Nuclear Structure

Studies in hadronic and semileptonic PV provide a unique probe of nuclear dynamics and hadron structure. The well-established program of PV measurements at MIT-Bates, JLab, and Mainz to look for strange quark vector currents in the nucleon offers a direct view of the low-energy sea-quark structure of the nucleon. The first results of this program have been reported in the past two years. As mentioned above, a PV experiment at JLab will provide the most precise, direct probe of the neutron distribution in a heavy nucleus. Looking to the future, improvements in cold neutron beam technology and polarized photon source developments open up new opportunities to separate the short and long range components of the PV NN weak interaction in few-body systems. Among the prospective experiments are:

- A measurement of the PV asymmetry in $\vec{n} + p \to d + \gamma$ at LANSCE. The asymmetry is dominated by the long range component of the PV, weak NN interaction. Its measurement would provide the first probe of this long range interaction in the two-nucleon sector.

- A measurement of the PV asymmetry $\vec{\gamma} + d \to n + p$ at JLab, which would probe the short range component of the PV, weak NN interaction. This measurement would complement studies of the short range PV NN interaction with $\vec{p}p$ scattering at TRIUMF and PSI.

- A measurement of the asymmetry for $\vec{n}$ spin rotation in ^{4}He at the NIST, which would also constrain the long range component of the PV, weak NN interaction. A follow up measurement with improved precision could also be carried out at the SNS.

- A measurement of the asymmetry for $\vec{\gamma} + p \to n\pi^+$ at JLab, which would probe the PV couplings that govern the long-range part of the PV NN interaction.

Completion of these measurements would address a number of open issues in the field, including the extent to which one can compute hadronic weak matrix elements, the applicability of effective field theory to few-body systems, medium effects on few-body parameters, and radiative corrections in semileptonic processes.

The field of hadronic PV is one where the disparity in experimental and theoretical progress is particularly acute. A number of theoretical issues remain to be addressed:

- In addition to measuring the weak charge of the cesium nucleus with atomic PV, the Boulder group also extracted a value of the ^{133}Cs anapole moment. The results appear to disagree with the implications of PV $\vec{p}+p$ elastic scattering and ^{18}F γ-decay for the long-range, π-exchange component of the PV NN interaction. The reasons behind this discrepancy are not understood. As the PV πNN coupling stands the best chance of any PV hadronic observable of being calculated from first principles in QCD, it is important to understand this discrepancy and derive a consistent value for the πNN coupling.

- There has been considerable recent theoretical interest in the application of chiral effective field theory to low-energy hadronic observables. The consequences for hadronic PV of this new approach remain to be fully worked out. It appears, however, that corrections to leading-order expressions for PV observables may be larger than previously anticipated. In the case of the PV πNN coupling which governs the long range PV NN interaction, the importance of these subleading corrections may reflect the importance of light sea quarks in weak matrix elements.

- The SAMPLE collaboration has recently performed a separation of the strange magnetic form factor, $G_{M^{(s)}}$, and the isovector axial form factor, $G_{A^{T=1}}$, with PV electron scattering. The axial form factor is subject to large electroweak radiative corrections. The experimental result suggests that the radiative corrections are considerably larger in magnitude than previously estimated theoretically. A resolution of this mystery is important not only for the SAMPLE measurement but also for one's understanding of semileptonic radiative corrections in other precision electroweak observables, such as neutron β-decay.

- A related problem involves the theoretical understanding of non-mesonic Λ hypernuclear decay. Measurements indicate that the ratio of neutron- to proton-induced decay rates is close to unity, whereas the theoretical expectation is for this ratio to be quite small.

4.7 Summary

Probing the physics of fundamental symmetries at low energy requires a broad compliment of facilities and experimental techniques. But with the exception of intense cold and ultracold neutron beams, the facilities are in place for the program outlined above. Support to operate the facilities and to do the experiments is crucial. The experimental manpower needed to carry out the program is comparable to that which is devoted to existing efforts in this subfield. New experiments begin after previous ones have been completed. However, the field is very much in need of additional theory support since the interpretation of many of the experiments must rely on detailed calculations.